PATENT COOPERATION TREATY

From the INTERNATIONAL BUREAU

PCT

NOTIFICATION OF ELECTION

(PCT Rule 61.2)

To:

Assistant Commissioner for Patents
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in its capacity as elected Office

Date of mailing (day/month/year) 13 June 2000 (13.06.00)	
International application No. PCT/GB99/03417	**Applicant's or agent's file reference** PA/GX98 PCT
International filing date (day/month/year) 15 October 1999 (15.10.99)	**Priority date** (day/month/year) 15 October 1998 (15.10.98)
Applicant CHUI, Kui, Ming	

1. The designated Office is hereby notified of its election made:

[X] in the demand filed with the International Preliminary Examining Authority on:

04 May 2000 (04.05.00)

[ ] in a notice effecting later election filed with the International Bureau on:

2. The election [X] was

[ ] was not

made before the expiration of 19 months from the priority date or, where Rule 32 applies, within the time limit under Rule 32.2(b).

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PATENT COOPERATION TREATY

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INTERNATIONAL SEARCH REPORT

(PCT Article 18 and Rules 43 and 44)

Applicant's or agent's file reference	**FOR FURTHER ACTION**	see Notification of Transmittal of International Search Report (Form PCT/ISA/220) as well as, where applicable, item 5 below.
PA/GX98 PCT		
International application No.	International filing date *(day/month/year)*	(Earliest) Priority Date *(day/month/year)*
PCT/GB 99/ 03417	15/10/1999	15/10/1998
Applicant		
CHUI, Kui, Ming		

This International Search Report has been prepared by this International Searching Authority and is transmitted to the applicant according to Article 18. A copy is being transmitted to the International Bureau.

This International Search Report consists of a total of 3 sheets.

[X] It is also accompanied by a copy of each prior art document cited in this report.

1. **Basis of the report**

   a. With regard to the **language,** the international search was carried out on the basis of the international application in the language in which it was filed, unless otherwise indicated under this item.

   [ ] the international search was carried out on the basis of a translation of the international application furnished to this Authority (Rule 23.1(b)).

   b. With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application, the international search was carried out on the basis of the sequence listing :

   [ ] contained in the international application in written form.

   [ ] filed together with the international application in computer readable form.

   [ ] furnished subsequently to this Authority in written form.

   [ ] furnished subsequently to this Authority in computer readble form.

   [ ] the statement that the subsequently furnished written sequence listing does not go beyond the disclosure in the international application as filed has been furnished.

   [ ] the statement that the information recorded in computer readable form is identical to the written sequence listing has been furnished

2. [ ] **Certain claims were found unsearchable** (See Box I).

3. [ ] **Unity of invention is lacking** (see Box II).

4. With regard to the **title,**

   [X] the text is approved as submitted by the applicant.

   [ ] the text has been established by this Authority to read as follows:

5. With regard to the **abstract,**

   [X] the text is approved as submitted by the applicant.

   [ ] the text has been established, according to Rule 38.2(b), by this Authority as it appears in Box III. The applicant may, within one month from the date of mailing of this international search report, submit comments to this Authority.

6. The figure of the **drawings** to be published with the abstract is Figure No. 2

   [X] as suggested by the applicant.

   [ ] because the applicant failed to suggest a figure.

   [ ] because this figure better characterizes the invention.

   [ ] None of the figures.

INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 99/03417

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G06T5/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G06T

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	ALPERIN N ET AL: "AUTOMATED ANALYSIS OF CORONARY LESIONS FROM CINEANGIOGRAMS USING VESSEL TRACKING AND ITERATIVE DECONVOLUTION TECHNIQUES" PROCEEDINGS OF THE COMPUTERS IN CARDIOLOGY MEETING,US,WASHINGTON, IEEE COMP. SOC. PRESS, vol. MEETING 16, October 1989 (1989-10), page 153-156 XP000147033 ISBN: 0-8186-2114-1	1,3,6,7, 12,14
A	abstract page 154, column 1, line 8 -column 2, line 4	2,13

-/--

[X] Further documents are listed in the continuation of box C.

[ ] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
31 January 2000	08/02/2000

Name and mailing address of the ISA	Authorized officer
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2

Form PCT/ISA/210 (second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 99/03417

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
A	CHARLAND P ET AL: "THE USE OF DECONVOLUTION AND TOTAL LEAST SQUARES IN RECOVERING A RADIATION DETECTOR LINE SPREAD FUNCTION" MEDICAL PHYSICS,US,AMERICAN INSTITUTE OF PHYSICS. NEW YORK, vol. 25, no. 2, February 1998 (1998-02), page 152-160 XP000833821 ISSN: 0094-2405 abstract page 154, column 1, line 9 - line 10 ---	1,5,12, 16
A	MARSUDI KISWORO ET AL: "2-D EDGE FEATURE EXTRACTION TO SUBPIXEL ACCURACY USING THE GENERALIZED ENERGY APPROACH" PROCEEDINGS OF THE INTERNATIONAL CONFERENCE ON EC3 - ENERGY, COMPUTER,COMMUNICATION AND CONTROL SYSTEMS (TENCON),US,NEW YORK, IEEE, vol. -, 2 August 1991 (1991-08-02), page 344-348 XP000333363 ISBN: 0-7803-0539-6 page 346, column 2, line 1 - line 2 -----	1,3,12, 13,15

2

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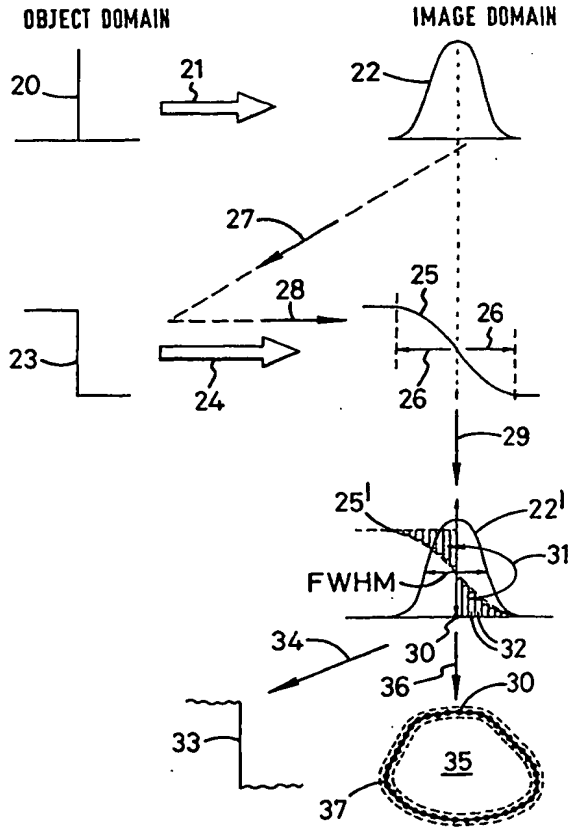
Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.

(54) Title: IMAGING

(57) Abstract

A de–convolution process is applied to an MR, CT or other image (25) of a scanned–object (23) to derive the point–spread function (22') at an object–edge and to pin–point from the mid–point of its full–width–half–maximum FWHM, the location (30) of the true image–edge. With the object–image (25') overlying the PSF function (22') in the de–convolution space, sub–pixels which follow location (30) are transferred to before it to re–construct the image–edge (25') for sharper conformity to the object–edge (23). Sharp definition of image–contour (37) facilitates accurate determination of area and volume of image profiles (35) and their segmentation. The accurate image–edge definition enables viable correction of geometrical distortion in stand–alone MR diagnosis and treatment planning.



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Imaging

This invention relates to imaging and in particular to methods and systems for image enhancement.

Imaging involves transfer from the object domain into the image domain, but owing to limiting factors such as the finite size of energy source, detector size, sampling frequency, display density, software filter function, and possibly partial-volume effects experienced with some imagers, an infinitely fine delta function in the object domain cannot be faithfully reproduced in the image domain. Instead, a smeared-out image, or point-spread function (PSF), is observed. Similarly, an infinitely sharp edge-response function (ERF) in the object domain becomes a smeared-out ERF in the image domain. The smearing effect becomes more intense as the adjacent ERFs of discontinuities or contrast profiles get closer to each other.

It is an object of the present invention to provide a method and system by which the above problem can be at least partly overcome.

According to one aspect of the present invention there is provided a method wherein a de-convolution process is applied to the image-domain results of an object-scan to derive therefrom the respective point- or line-spread function effective in the object- to image-domain transfer of one or more object-discontinuities, and to derive from said function the location in the image domain of the respective discontinuity.

According to another aspect of the invention there is provided an imaging system comprising means for

performing a de-convolution process on the image-domain results of an object-scan to derive therefrom the respective point- or line-spread function effective in the object- to image-domain transfer of one or more object-discontinuities, and means to derive from said function the location in the image domain of the respective discontinuity.

The method and system of the invention enable the location of the respective discontinuity in the image domain, to be established with a high degree of accuracy. This is critical to image definition free of any substantial smearing, and to this end the location of the respective discontinuity may be derived to sub-pixel accuracy simply from the mid-point of the full-width half-maximum of said function.

The said function may be correlated with the image-domain results of said transfer for enhancement of spatial resolution of the imaging of the one or more discontinuities. This enhancement may involve transfer of sub-pixels within the image-domain results of the respective one or more discontinuities, the sub-pixels being transferred within their respective image-domain results from one side to the other of said location.

The de-convolution process may be carried out using least-squares running filtering.

An imaging method and system according to the present invention will now be described, by way of example, with reference to the accompanying drawings, in which:

Figure 1 illustrates schematically the method and system of the invention;

Figure 2 illustrates features of processing performed in the method and system of Figure 1;

Figure 3 shows results achieved from use of the method and system of Figure 1;

Figure 4 shows to an enlarged scale a section of the contour of an image profile depicted in Figure 2;

Figures 5 and 6 are a plan view and sectional end-elevation of a couch-top used in the method and system of Figure 1; and

Figure 7 provides illustrates of a convolution operation, as a basis for a mathematical model of de-convolution processing in accordance with the method and system of Figure 1.

The method and system to be described with reference to Figure 1 utilise MR scanning for medical diagnostic and treatment-planning purposes. In principle and in the general techniques described, the method and system of the invention can be used in other applications of MR scanning and also in circumstances where other scanning techniques are utilised. Furthermore, although both structure and function are represented by discrete 'boxes' 1 to 19 in Figure 1, the method and system are to a substantial extent manifest in programmed digital data-processing operations.

Referring to Figure 1, data derived in accordance with conventional operation of an MR scanner 1 is processed for imaging purposes within a processor 2. The output of the processor 2 is used to provide a display 3, and from this is subject to post-imaging processing 4. The post-imaging processing 4 includes the facility for selecting

a region of the display 3 for more-detailed and closer inspection.

To the extent the imaging method and system of Figure 1 have so far been described, they are conventional, and it is in further processing 5 of the image data of the selected region of interest obtained by the post-imaging processing 4 that a step forward from what is already known is achieved. More particularly, the further processing 5 is operative to define more clearly the true edges or boundaries of image contour(s) in the selected region of interest, and to enhance the accuracy of the imaging of those contours.

The definition and accuracy of transfer of features from the object domain scanned by the scanner 1, to the image domain manifest in the post-imaging processing 4, is limited by many factors. The limitations arise from within the scanner 1 itself (in particular the finite size of the energy source), within the processing performed by the processor 2, and within the display 3; limitations arise inherently from, for example, the data sampling frequency and display density used, and also from the filter-function of the software involved. More particularly, and referring to Figure 2, an infinitely fine delta function 20 in the object domain is not faithfully reproduced in the image domain. Instead, the transfer as represented by the arrow 21 results in a point-spread function (PSF) or smeared-out image 22 in the image domain. Similarly, an infinitely sharp edge-response function (ERF) or step 23 in the object domain becomes through the transfer represented by arrow 24, a smeared-out transition 25 of spread represented by dimension arrows 26, in the image domain. When two image ERFs are close to one another, the smeared-out effects run into each other. The consequent deterioration of the spatial resolution is often monitored by the percentage

modulation transfer which is given by the ratio, expressed as a percentage, of the amplitude of the modulation in the image domain to that in the object domain.

The smearing effect becomes more intense as adjacent ERFs of discontinuities or contrast profiles get closer to each other (or as the spatial frequency of the modulation becomes higher); this also causes loss of profile height. The inherent loss of the spatial resolution (that is, the part that is indicated by the smeared-out effect on the corner edge of the ERF) cannot be restored or partially restored even by re-scanning the image with an ultra high resolution digital scanner system.

The further processing 5 is operative in accordance with the invention to provide accurate image-edge definition and location, and to improve spatial resolution in the imaging. More especially, in the context of Figure 2, the edge position corresponding to the discontinuity or step 23 of the object ERF is pin-pointed in the image domain from the mid-point of the full-width half-maximum (FWHM) of the image PSF; the pin-pointing may be to sub-pixel accuracy for the image ERF. In a practical implementation, low-contrast filtering, 'area' filtering, and sub-pixel sampling may be used to remove the 'spurious' edges and other features of the single-pixel modulation. The discontinuity or step 23 of the ERF is then restored within the image domain by removing the sub-pixel values from outside the optimum edge position to compensate for those within. It is to be noted that the sub-pixels then become pixels in display, and that the enhancement is equivalent to the performance of an extra high resolution image transfer system.

As represented in Figure 2 by the arrows 27 and 28, the image ERF 25 of an infinitely-sharp ERF 23 can be

produced by convolution of the image PSF 22 with the object ERF 23. In accordance with the present invention, de-convolution of the image ERF 25 represented by the arrow 29 reproduces the image PSF 22 in a de-convolution space as image PSF 22'. The image ERF 25 is superimposed on the PSF 22' within this space as image ERF 25', and the optimum edge-position 30 is derived from the mid-point of the FWHM of the image PSF 22', and is pin-pointed to sub-pixel accuracy.

For one-dimensional cases, the operation in accordance with the invention is relatively simple, as only either the x- or the y-profile, that is to say a line spread function LSF is involved. But for two-dimensional operations, both the x- and y-profiles, and if necessary, the xy-diagonal profiles to eliminate any possible streakings in the image, may be used; in this case, a proper weighting scheme will be required to re-construct the image.

Once the original sharp-edge feature represented by the object ERF 23 is pin-pointed at the position 30 within further processing 5, that feature may be restored by additional re-processing 6 (Figure 1). In re-processing 6, the sub-pixel values occurring 'outside' the optimum edge-position 30 are transferred to compensate those 'within'. This is illustrated in Figure 2 by arrow 31 transferring sub-pixel blocks 32 from after point 30 in the image ERF 25', to before it. The re-construction of image ERF 25' into image ERF 33 conforming closely in configuration to object ERF 23 is represented by arrow 34. Image ERF 33 is displayed in enlarged form in display 7 (Figure 1).

These techniques enable substantial recovery of the loss of spatial resolution in the imaging, without the trade-off loss of other properties such as image noise.

Furthermore, the enhancement of spatial resolution in display 7 reproduces the region of interest selected from display 3, without blurring (or step) effects at the profile edge.

Figure 3 is illustrative of some of the low-contrast results provided in practice from MR scanning of a pig's brain in fluid. Curve A is the image ERF produced, whereas curve B is the line spread function (LSF) resulting from de-convolution of curve A carried out in processing 5. The optimum edge-position is established from the mid-point C of the FWHM of curve B, and the additional re-processing 6 is operative by means of sub-pixel transfer, to re-construct curve A to conforms substantially to the edge-feature from which it originated in the display 7.

It is to be noted that whereas curve A is stepped, curve B is nonetheless smooth and that mid-point C is located to sub-pixel accuracy. Furthermore curve B indicates a sensitivity of more than 8:1 between the profile-height and background noise.

Referring again to Figure 2, the complete profile 35 of an image within the selected area of interest of display 3, is built up as indicated by arrow 36, from the edge-position data derived within processing 5. This data identifies the location of the point 30, together with the locations of all corresponding points derived from sampling the multiple x- or y-profiles of the selected area of interest. The build up and display of these points from the data takes place in display 8 so that a substantially true contour 37 for the profile 35 is defined. The sharpness of the true contour 37 is in contrast to the smeared contour that without de-convolution would have been obtained by virtue of the

spread (represented by the arrows 26) of the relevant image ERFs 25.

A small portion of the contour 37 is shown enlarged in Figure 4 and is defined as a best-fit line between optimum edge-positions derived respectively from x- and y-profiles; the x-profile positions are indicated by black dots and the y-profile positions by white dots. The closeness to one another of corresponding positions in the x- and y-profiles is indicative of the accuracy to sub-pixel level achieved. The smear-out that would have been manifest in the image-profile contour if the de-convolution technique were not used, would have extended throughout the space bounded by the dashed lines 38 and 39; these boundaries are indicated in dashed line in the representation of profile 35 in Figure 2.

The accurate definition of the image contour 37 derived in the display 8 allows correspondingly accurate determination in calculation 9 of the area within that contour; the volume involved can also be derived from successive slices scanned. The determination of area and volume is especially useful for diagnostic and accurate assessment 10 of the size of a tumour or lesion before and after treatment. It is similarly useful for assessment of arterial dimensions in angiography.

Moreover, the accurate definition of the image contour 37 derived in the display 8, is particularly useful for segmenting anatomical structures for diagnostic and treatment planning 11. Furthermore, the ratio of intensities of two scans are derived by processing 12 to derive values of relaxation times T_1 and T_2, and of proton density. The values are then represented in display 13 within the boundary of the image contour, utilising standardisation data derived from a couch-top 14 used within the scanner 1. The couch-top 14, which also

provides landmarks for determining position coordinates, has the form shown in Figures 5 and 6, and will now be described.

Referring to Figures 5 and 6, the couch-top 40, which is of polystyrene bubble foam, has the form of a flat slab, and is supported on a curved foam base 41 that fits to the scanner table of the MR installation. Two zig-zag runs of tubing 42 are embedded within the top 40 to extend along the length of the couch either side of centrally-embedded straight tubing 43.

The tubing 42 of each zig-zag run is of double-bore rectangular cross-section, whereas the tubing 43 is of single-bore cross-section. The five bores defined by the array of tubing 42 and 43 may be filled respectively with the five MR solutions S_0 to S_4 of Table I, for standardisation and calibration purposes. The four $MnCl_2.4H_2O$ solutions, S_1 to S_4, cover the full range of values of T_1 and T_2 for anatomical tissues, and the fifth solution, S_0, of $CuSO_4.5H_2O$, is nominally equivalent to "loosely bound water".

Table I

Solution		T_1 at 0.5T	T_2 at 0.5T
S_0	1.25 g/l $CuSO_4.5H_2O$	200 ms	200 ms
S_1	3.41×10^{16} Mn^{+2} ions/ml	840 ms	300 ms
S_2	1.15×10^{17} Mn^{+2} ions/ml	440 ms	120 ms
S_3	2.30×10^{17} Mn^{+2} ions/ml	250 ms	60 ms
S_4	4.37×10^{17} Mn^{+2} ions/ml	150 ms	30 ms

The tissue types revealed by the T_1, T_2 and proton density values in display 13 are determined by processing 15 from look-up tables, and tissue densities are assigned within the image-contour boundaries in display 16. The images of display 16 are furthermore corrected empirically for geometry distortion in accordance with data supplied from memory 17. The data stored in memory 17 is derived using a set of drum phantoms of the spider-web form, and correction for geometry distortion is realistically effective principally because of the accuracy and spatial resolution with which image-contours are defined.

The tissue types assigned to the corrected images are utilised in display 16 through the Bulk Heterogeneity Correction method described by Richard A, Geise *et al*, Radiology, 124:133-141, July, 1977, to establish for each image a normalised tissue density value; the up-datable look-up table for this is stored in memory 18. Accordingly, the display 16 when used at step 19 in conjunction with the positional datums derived from the couch 14, has all the tissue contours accurately mapped out with their respective tissue densities and locations. This establishes an accurate and readily-usable, stand-alone basis for diagnosis and treatment planning, and enables a true three-dimensional assessment and plan to be made when both orthogonal and oblique MR images are involved.

Although the method and system of the invention have been described above in the medical context they are applicable more widely than this, for example, in engineering, in physical science and in the field of instrumentation generally. Moreover, the method and system is not limited to MR imaging, but may be utilised where other forms of imaging are involved. The steps and structure represented in Figure 1 by 'boxes' 1 to 11 are just as applicable to computer assisted tomography (CT),

as they are to MR imaging. Other forms of imaging to which the invention is applicable include X-ray radiography, film- or print-image transformation to digital form, digital X-ray fluorography, ultra-sound imaging, nuclear medicine, positron emission tomography (PET) and other camera or imaging. The technique is particularly suitable for use in X-ray digital fluorography, in which small structures under study are highlighted by injection of contrast liquids; the small structures may also be isolated from surrounding interfering effects by using an image subtraction technique.

The inherent resolutions of X-ray radiography, ultra-sound imaging, nuclear medicine, and PET scanning are relatively low, and some are used for real-time study. Only the individual still frame or hard-copy images may be re-processed.

In the context of engineering, physical science and the field of instrumentation, the invention is applicable to one-dimensional imaging as used, for example, in regard to bar-code patterns, the spectrum of DNA analysis, iris patterns of eyes (for example, for identification purposes in commercial banking), finger-print identification, and emission spectroscopy. The invention is also applicable to two-dimensional imaging, for example, in relation to images obtained by satellite or pattern recognition, or from a surveillance camera or during laboratory experimentation. As a general matter, the invention is applicable where there needs to be accurate determination of the edge position in an image *versus* the true object-edge position, for the purpose, for example, of measurement of the positional displacement between object and image, distortion correction and manufacturing control.

As a further example of application of the present invention, a method and system that uses CT and MR imaging in conjunction with one another, will now be described.

The major contribution to the magnetic-resonance (MR) signal comes from the abundant protons content of water molecules and protein. It is a quantum process at the Larmor frequency according to the magnetic field in use. The 'T_1-weighted' and 'T_2-weighted' MR signals from protons provide contrast numbers that are relative in scale, whereas in CT, the X-ray absorption is a polychromatic attenuation process affected by the electron densities of all the atoms presented within the X-ray beam. There is no equation to correlate the CT number (or the linear attenuation coefficient, electron density, or tissue density) with the MR-contrast numbers; no direct calibration between the two types of signal is possible. This lack of correlation is confirmed by consideration of bone and air which are at opposite ends of the CT contrast (absolute) scale using water as the base-line reference, but which are at the same end of the MR-image contrast (relative) scale owing to their common low proton-population.

The lack of correlation between the CT and MR signals acts against their use in combination for imaging purposes, but the present invention provides a method and system by which the advantages of each may be utilised to improve image resolution and contrast information.

In the latter regard, CT provides a high spatial resolution but only in regard to view normal to the transverse slice. Resolution for all re-constructed non-transverse planes is poor owing to the need to use elongate voxels to improve signal-to-noise ratio. Also, the partial-volume effect of using elongate voxels may

give rise to detection errors at the thin edge of a contrast profile of a lesion. MR, on the other hand, can give the same high degree of spatial resolution viewed in the normal direction to any image-slice plane, and can also provide isotropic resolution with cubic-voxel volume imaging.

To this end, multiple-slice transverse CT scans are collected across a section of the volume of interest in a patient or other subject. Corresponding multiple-slice transverse MR scans of the same volume are also collected. The slice thickness of the latter scans may be one half, or smaller, of the thickness of the CT slices, and may be collected two-dimensionally or three-dimensionally. The patient or other object scanned is constrained throughout on a couch that provides landmarks with respect to a coordinate reference arrangement on the couch-top. This is to ensure the reproducibility of, for example, anatomical positions and features to the first order accuracy for the corresponding CT and MR scans, and possibly for radiation treatment to be made.

The respective transverse planes of the CT and MR images are processed individually in the method and are matched with one another in a de-convoluted space for the CT and MR images. The two sets of de-convoluted maps are then merged together to a second order of accuracy in order that the CT numbers may be transferred over to replace the corresponding MR contrast numbers. Once this has been achieved, non-transverse (or oblique) planes can be obtained from the two-dimensional MR images, or from the re-arrangement of the corresponding voxels of the three-dimensional volume images; where two-dimensional MR is used, a further step of contrast transformation may be required.

The respective transverse planes of CT and MR images are processed individually by using 'boundary' or 'finger-print' matching techniques in a de-convolution space for the CT & MR images. In these transverse image planes, in particular when used medically, the skin-contour features along the sides of the patient may be best used for second-order alignment and matching purposes, as they are less affected by patient-movements. Transitional error may be readily corrected with respect to the coordinate positions of a rectangular tubing system embedded in the couch-top (for example that described above with reference to Figures 5 and 6). The processed data may then be used for a 'diagnostic and statistics software package' of CT image *versus* MR image for their exactly corresponding transverse slice(s), and an associated 'statistical package' for accurate computation of the 'true' area, and then the 'true' volume, of a lesion or tissue profile or contour.

The two sets of de-convoluted maps may also be merged together to a second order of accuracy in order that the CT numbers may be transferred over to replace the corresponding MR contrast numbers. Once this has been done, non-transverse (or oblique) planes are obtained from the two-dimensional image or from the re-arrangement of the corresponding voxels of the three-dimensional volume; in the two-dimensional MR case, a further step of contrast transformation is required. The transferred contrast data may then be used in a three-dimensional radiotherapy treatment planning software package for an in-plane, oblique-image pseudo-three-dimensional approach using MR images.

Software required for de-convolution processing of image data according to the invention may be implemented in conjunction with a least-squares curve-fitting method. A mathematical model of the method, from which the required

software can be readily developed, will now be given in relation to Figure 7 which indicates the convolution of an LSF L(x) with a step function SF having a step-down edge SDE, to produce an image ERF E(x). Considering the values of E(x) resulting from the convolution at points x=1 to x=n of SF:

at x=1:

$$\sum_{0}^{a} L(x)\,\Delta x = E(x)_1$$

at x=2:

$$\sum_{0}^{a} L(x)\,\Delta x - \sum_{a-1}^{a} L(x)\,\Delta x = E(x)_2$$

at x=3:

$$\sum_{0}^{a} L(x)\,\Delta x - \sum_{a-2}^{a} L(x)\,\Delta x = E(x)_3$$

until at x=n:

$$\sum_{0}^{a} L(x)\,\Delta x - \sum_{1}^{a} L(x)\,\Delta x = E(x)_n$$

For de-convolution, that is to say, for the ERF E(x) to manifest the LSF L(x):

$$E(x)_1 - E(x)_2 = \sum_{a-1}^{a} L(x)\,\Delta x = L(x)_{(a-1)-a}\,\Delta x$$

$$\{E(x)_1 - E(x)_2\}/\Delta x = L(x)_{(a-1)-a}$$

thus:

$$\{E(x)_2 - E(x)_3\}/\Delta x = L(x)_{(a-2)-(a-1)}$$

leading to

$$\{E(x)_{(n-1)} - E(x)_n\}/\Delta x = L(x)_{(n-1)-n}$$

Thus, the same shape of LSF is recovered by the de-convolution process independently of the sense of the ERF; it does not matter whether a roll-up or a roll-down ERF of a positive or a negative contrast profile, is involved. This is an important property as a positive contrast contour will have roll-up (from low to high) ERFs at both ends whereas a negative contrast contour will have roll-down (from high to low) ERFs at both ends.

In the practical implementation, the LSF is derived from the ERF by de-convolution using a running filter. This enhances the accuracy of the method in overcoming the problem of noise that affects the digitised pixel values of the image. Use is made of a least-squares fitting of a set of data points that advances along the whole length of the function from one point to another.

Assuming that $y = a_0 + a_1x + a_2x^2$ represents the ERF curve a five-point or seven-point fit is used, and the normal equation becomes:

$$\begin{vmatrix} \Sigma 1 & \Sigma x_i & \Sigma x_i^2 \\ \Sigma x_i & \Sigma x_i^2 & \Sigma x_i^3 \\ \Sigma x_i^2 & \Sigma x_i^3 & \Sigma x_i^4 \end{vmatrix} \begin{vmatrix} a0 \\ a1 \\ a2 \end{vmatrix} = \begin{vmatrix} \Sigma y_i \\ \Sigma x_i y_i \\ \Sigma x_i^2 y_i \end{vmatrix}$$

where: i is 1+n, ... 5+n; ... until m-5, ... m
or
i is 1+n, ... 7+n; ... until m-7, ... m
n is 0,1, 2, ... ; and
1, ... m is the span of the ERF profile.

The solution may be derived from either:

$$\begin{vmatrix} a0 \\ a1 \\ a2 \end{vmatrix} = \begin{vmatrix} \Sigma 1 & \Sigma x & \Sigma x^2 \\ \Sigma x & \Sigma x^2 & \Sigma x^3 \\ \Sigma x^2 & \Sigma x^3 & \Sigma x^4 \end{vmatrix}^{-1} \begin{vmatrix} \Sigma y \\ \Sigma xy \\ \Sigma x^2 y \end{vmatrix}$$

or:

$$\frac{a0}{\begin{vmatrix} \Sigma y & \Sigma x & \Sigma x^2 \\ \Sigma xy & \Sigma x^2 & \Sigma x^3 \\ \Sigma x^2 y & \Sigma x^3 & \Sigma x^4 \end{vmatrix}} = \frac{a1}{\begin{vmatrix} \Sigma 1 & \Sigma y & \Sigma x^2 \\ \Sigma x & \Sigma xy & \Sigma x^3 \\ \Sigma x^2 & \Sigma x^2 y & \Sigma x^4 \end{vmatrix}} = \frac{a2}{\begin{vmatrix} \Sigma 1 & \Sigma x & \Sigma y \\ \Sigma x & \Sigma x^2 & \Sigma xy \\ \Sigma x^2 & \Sigma x^3 & \Sigma x^2 y \end{vmatrix}} = \frac{1}{\begin{vmatrix} \Sigma 1 & \Sigma x & \Sigma x^2 \\ \Sigma x & \Sigma x^2 & \Sigma x^3 \\ \Sigma x^2 & \Sigma x^3 & \Sigma x^4 \end{vmatrix}}$$

For both of these equations to be valid:-

$$\begin{vmatrix} \Sigma 1 & \Sigma x & \Sigma x^2 \\ \Sigma x & \Sigma x^2 & \Sigma x^3 \\ \Sigma x^2 & \Sigma x^3 & \Sigma x^4 \end{vmatrix} \neq 0$$

The gradient at $dy/dx_{(3+n)}$ or $dy/dx_{(4+n)}$ can then be derived and plotted against x for the LSF profile.

The graph of dy/dx against x gives the LSF profile. The peak of this profile is located centrally of the mid-points of the ascending and descending limbs of the graph. These points define the extremes of the full-width-half-maximum (FWHM) of the profile and the mid-point of this is determined with an accuracy of sub-pixel level owing to the 'average' effect.

The point spread function (PSF) is the two dimensional profile which may be derived, in practice, from the two corresponding LSFs orthogonal to one another within an image plane. The peak position of the PSF profile is, therefore, from the 'mean' or 'cross-over' of the two peaks or the two LSF profiles. The PSF is obtained in practice from two orthogonal axes in a two-dimensional plane.

The generation of the LSF (or PSF) is, after phase-reversal correction, independent of the roll-up or roll-down nature of ERFs at the edges of the contrast contour. In other words, it is independent of the sense and the absolute value of the contrast numbers within the

contour. The peak position of the LSF (or PSF) is the central half-way (50%) point of the roll-up or roll-down ERF which is the optimum position for true-edge definition.

Claims:

1. A method of imaging wherein a de-convolution process is applied to the image-domain results of an object-scan to derive therefrom the respective point- or line-spread function effective in the object- to image-domain transfer of one or more object-discontinuities, and to derive from said function the location in the image domain of the respective discontinuity.

2. A method according to Claim 1 wherein the location of the respective discontinuity is derived from the mid-point of the full-width half-maximum of said function.

3. A method according to Claim 1 or Claim 2 wherein said function is correlated with the image-domain results of said transfer for enhancement of spatial resolution of the imaging of the one or more discontinuities.

4. A method according to Claim 3 wherein the enhancement of spatial resolution of the imaging of the one or more discontinuities involves transfer of sub-pixels within the image-domain results of the respective one or more discontinuities, the sub-pixels being transferred within their respective image-domain results from one side to the other of said location.

5. A method according to any one of Claims 1 to 4 wherein the de-convolution process is carried out using least-squares running filtering.

6. A method according to any one of Claims 1 to 5 wherein an edge-contour of the object is defined in the image domain using de-convolution processing as aforesaid.

7. A method according to Claim 6 wherein the area and/or volume of the object-image within the edge-contour is determined.

8. A method according to Claim 6 or Claim 7 wherein the object-scan is a magnetic resonance (MR) scan, values of relaxation times T_1 and T_2 are derived for the object-image within said contour, and these values are used to identify from stored data, types of tissue or other material involved in the scanned object.

9. A method according to Claim 8 wherein density values for the identified tissue or other material types are derived from further stored data.

10. A method of imaging according to any one of Claims 1 to 9 wherein corresponding computed tomography (CT) and magnetic resonance (MR) scans of the same part of an object are derived, the scans are related to one another for correlation of one to the other positionally with respect to said part using the de-convolution process, and imaging of said part of the object is provided in accordance with the MR scan as modified spatially in dependence upon the CT contrast numbers applicable to the corresponding, correlated positions of the CT scan.

11. A method according to any one of Claims 8 to 10 wherein geometric correction is applied to the imaging derived from the MR scan, in accordance with stored data.

12. An imaging system comprising means for performing a de-convolution process on the image-domain results of an object-scan to derive therefrom the respective point- or line-spread function effective in the object- to image-domain transfer of one or more object-discontinuities, and means to derive from said function the location in the image domain of the respective discontinuity.

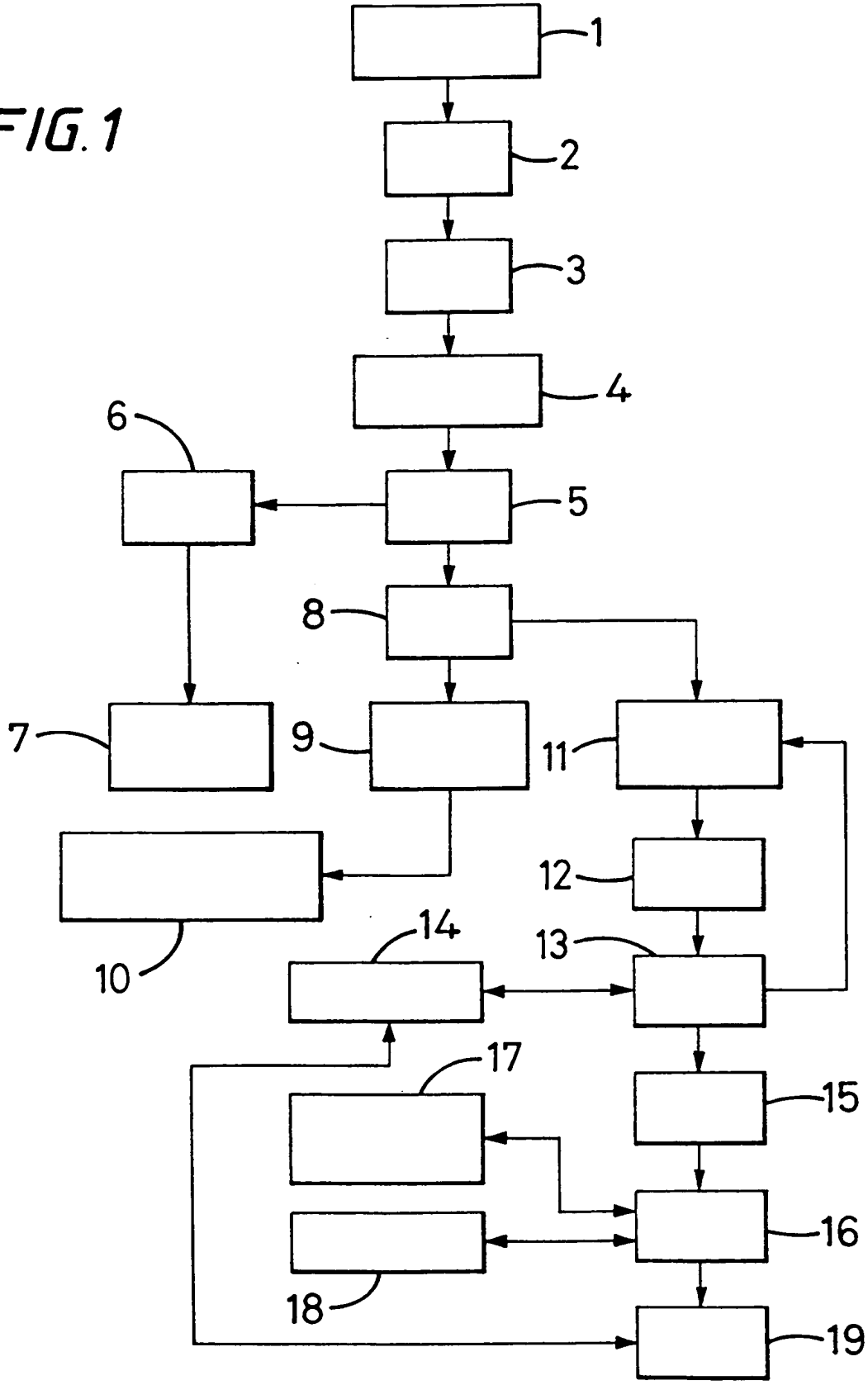
13. A system according to Claim 12 wherein the location of the respective discontinuity is derived from the mid-point of the full-width half-maximum of said function.

14. A system according to Claim 12 or Claim 13 wherein said function is correlated with the image-domain results of said transfer for enhancement of spatial resolution of the imaging of the one or more discontinuities.

15. A method according to Claim 14 wherein the enhancement of spatial resolution of the imaging of the one or more discontinuities involves transfer of sub-pixels within the image-domain results of the respective one or more discontinuities, the sub-pixels being transferred within their respective image-domain results from one side to the other of said location.

16. A system according to any one of Claims 12 to 15 wherein the de-convolution process is carried out using least-squares running filtering.

FIG. 1



2/6

FIG. 2

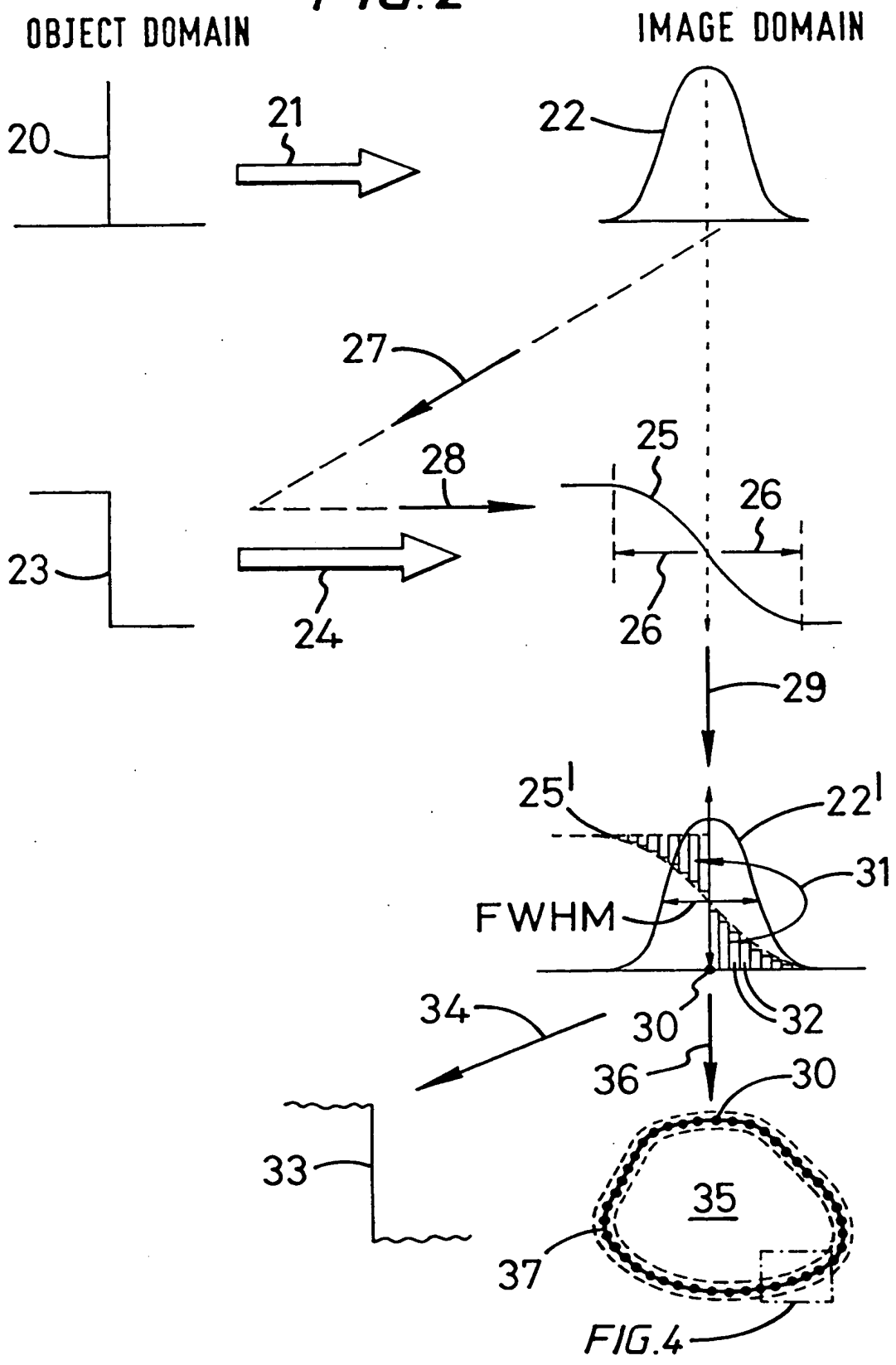

OBJECT DOMAIN
IMAGE DOMAIN
20
21
22
27
28
25
26
23
24
26
29
25'
22'
31
FWHM
34
30
32
36
30
33
35
37

FIG. 4

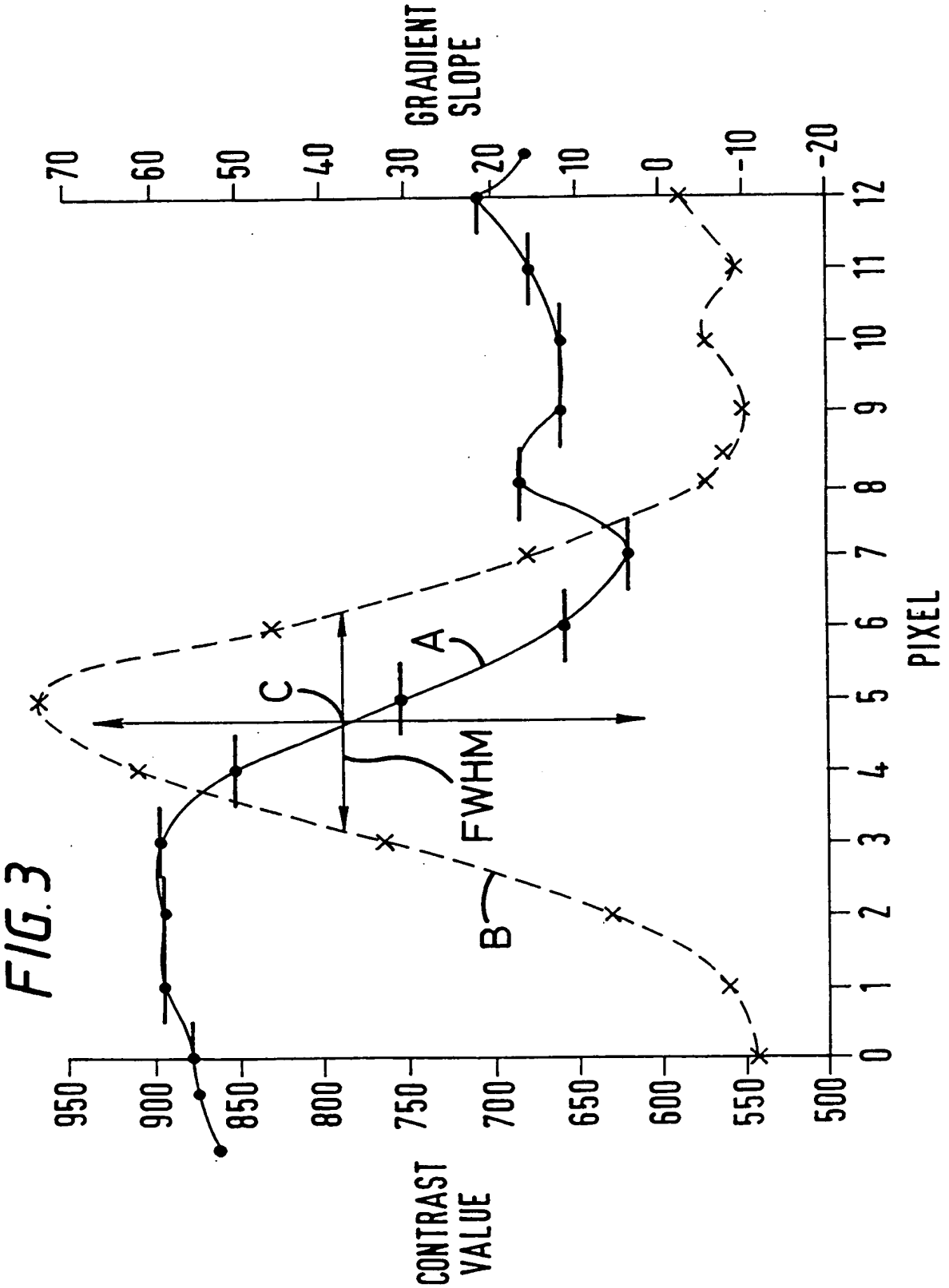

GRADIENT SLOPE
70
60
50
40
30
20
10
0
-10
-20
12
11
10
9
8
7
6
5
4
3
2
1
0
PIXEL
950
900
850
800
750
700
650
600
550
500
CONTRAST VALUE
A
B
C
FWHM

FIG. 3

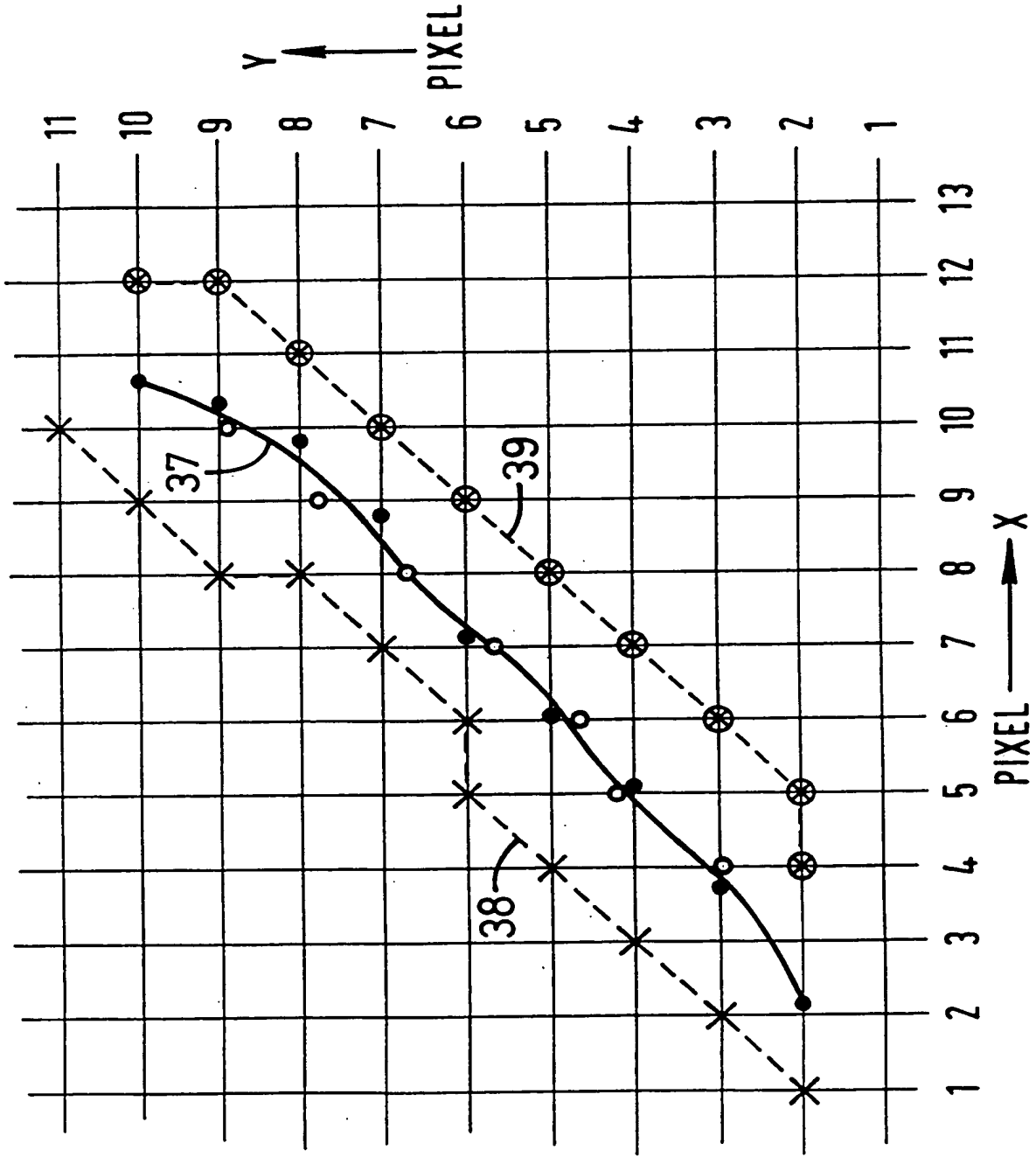
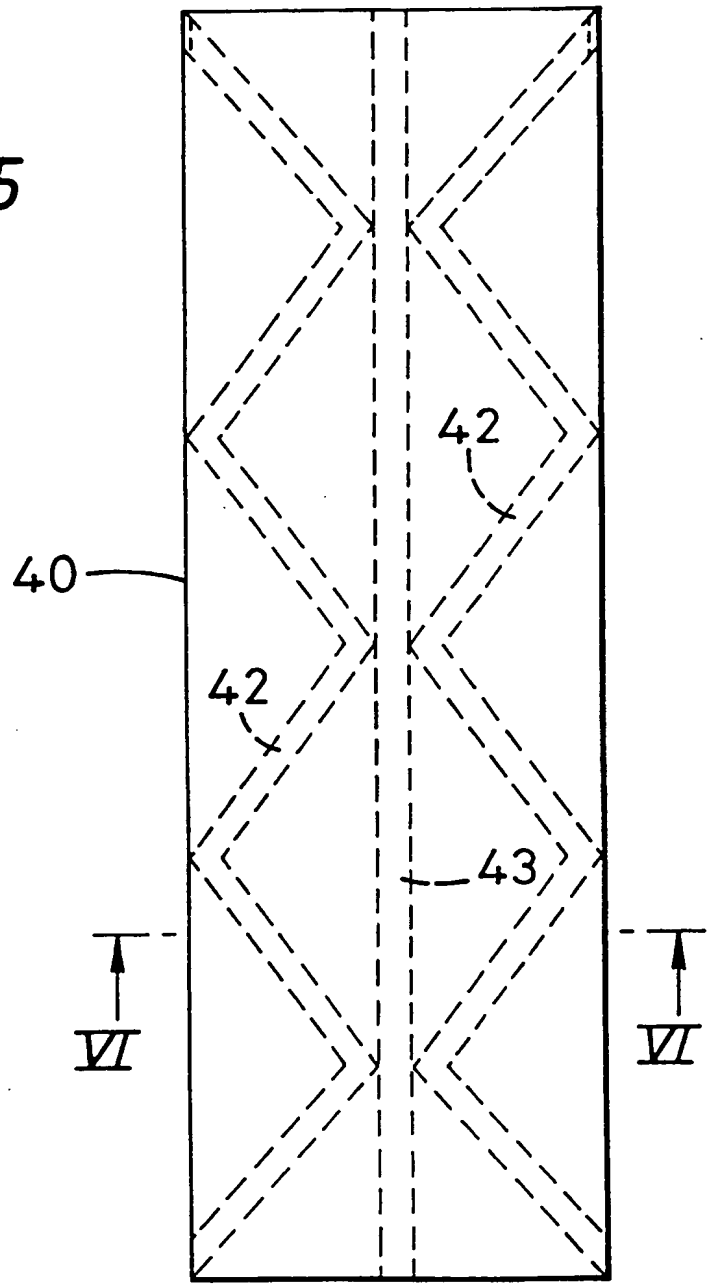


FIG. 4

FIG. 5



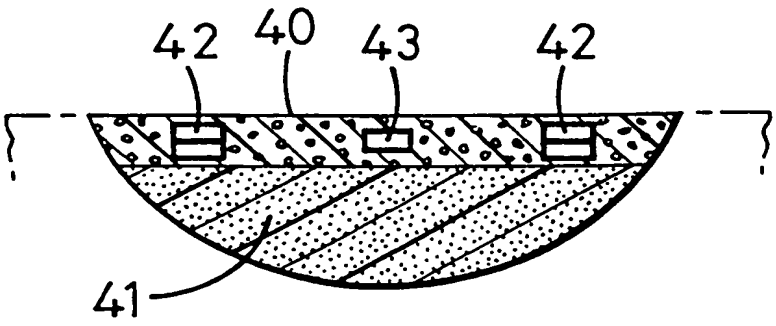


FIG. 6

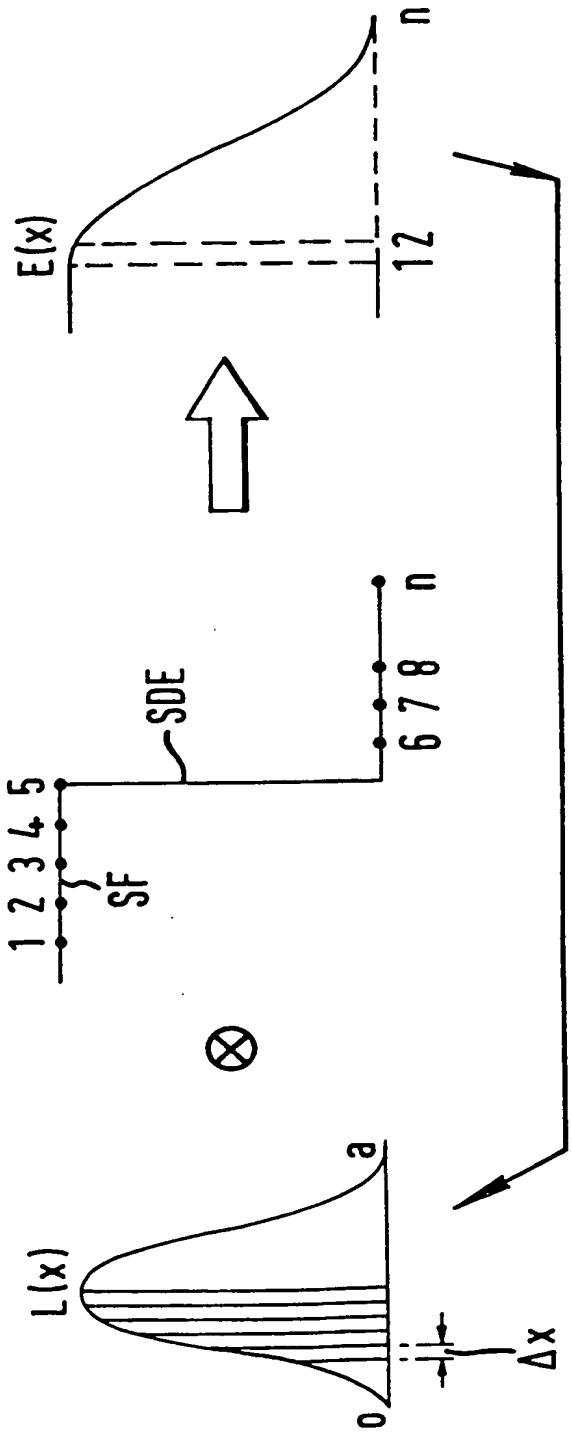


FIG.7

PATENT COOPERATION TREATY

PCT

INTERNATIONAL PRELIMINARY EXAMINATION REPORT

(PCT Article 36 and Rule 70)

Applicant's or agent's file reference	FOR FURTHER ACTION	See Notification of Transmittal of International Preliminary Examination Report (Form PCT/IPEA/416)
PA/GX98 PCT		
International application No.	International filing date *(day/month/year)*	Priority date *(day/month/year)*
PCT/GB99/03417	15/10/1999	15/10/1998
International Patent Classification (IPC) or national classification and IPC G06T5/00		
Applicant CHUI, Kui, Ming		

1. This international preliminary examination report has been prepared by this International Preliminary Examining Authority and is transmitted to the applicant according to Article 36.

2. This REPORT consists of a total of 6 sheets, including this cover sheet.

   ☒ This report is also accompanied by ANNEXES, i.e. sheets of the description, claims and/or drawings which have been amended and are the basis for this report and/or sheets containing rectifications made before this Authority (see Rule 70.16 and Section 607 of the Administrative Instructions under the PCT).

   These annexes consist of a total of 9 sheets.

3. This report contains indications relating to the following items:

   - I ☒ Basis of the report
   - II ☐ Priority
   - III ☐ Non-establishment of opinion with regard to novelty, inventive step and industrial applicability
   - IV ☐ Lack of unity of invention
   - V ☒ Reasoned statement under Article 35(2) with regard to novelty, inventive step or industrial applicability; citations and explanations suporting such statement
   - VI ☐ Certain documents cited
   - VII ☐ Certain defects in the international application
   - VIII ☒ Certain observations on the international application

Date of submission of the demand	Date of completion of this report
04/05/2000	07.02.2001
Name and mailing address of the international preliminary examining authority: European Patent Office D-80298 Munich Tel. +49 89 2399 - 0 Tx: 523656 epmu d Fax: +49 89 2399 - 4465	Authorized officer Meinl, W Telephone No. +49 89 2399 2532

Form PCT/IPEA/409 (cover sheet) (January 1994)

INTERNATIONAL PRELIMINARY EXAMINATION REPORT

International application No. PCT/GB99/03417

I. Basis of the report

1. This report has been drawn on the basis of *(substitute sheets which have been furnished to the receiving Office in response to an invitation under Article 14 are referred to in this report as "originally filed" and are not annexed to the report since they do not contain amendments (Rules 70.16 and 70.17).)*:
Description, pages:

3,4,8-18	as originally filed			
1,2,5-7	as received on	22/11/2000	with letter of	18/11/2000

Claims, No.:

1-16	as received on	22/11/2000	with letter of	18/11/2000

Drawings, sheets:

1,2,4-6	as originally filed			
3	as received on	22/11/2000	with letter of	18/11/2000

2. With regard to the **language**, all the elements marked above were available or furnished to this Authority in the language in which the international application was filed, unless otherwise indicated under this item.

   These elements were available or furnished to this Authority in the following language: , which is:

   - ☐ the language of a translation furnished for the purposes of the international search (under Rule 23.1(b)).
   - ☐ the language of publication of the international application (under Rule 48.3(b)).
   - ☐ the language of a translation furnished for the purposes of international preliminary examination (under Rule 55.2 and/or 55.3).

3. With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application, the international preliminary examination was carried out on the basis of the sequence listing:

   - ☐ contained in the international application in written form.
   - ☐ filed together with the international application in computer readable form.
   - ☐ furnished subsequently to this Authority in written form.
   - ☐ furnished subsequently to this Authority in computer readable form.
   - ☐ The statement that the subsequently furnished written sequence listing does not go beyond the disclosure in the international application as filed has been furnished.
   - ☐ The statement that the information recorded in computer readable form is identical to the written sequence listing has been furnished.

4. The amendments have resulted in the cancellation of:

   ☐ the description, pages:

   ☐ the claims, Nos.:

   ☐ the drawings, sheets:

5. ☐ This report has been established as if (some of) the amendments had not been made, since they have been considered to go beyond the disclosure as filed (Rule 70.2(c)):

   (Any replacement sheet containing such amendments must be referred to under item 1 and annexed to this report.)

6. Additional observations, if necessary:

V. Reasoned statement under Article 35(2) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement

1. Statement

Novelty (N)	Yes:	Claims	4,15
	No:	Claims	1-3, 6-7, 12-14, 16
Inventive step (IS)	Yes:	Claims	4,15
	No:	Claims	5, 8-11
Industrial applicability (IA)	Yes:	Claims	1-16
	No:	Claims	

2. Citations and explanations
   see separate sheet

VIII. Certain observations on the international application

The following observations on the clarity of the claims, description, and drawings or on the question whether the claims are fully supported by the description, are made:
see separate sheet

Re. Sections V, VIII (Novelty, Inventive step, Observations)

1. The following documents are referred to in this report:-

   D1 - D3: The documents of the International Search Report in the order as they are listed therein.

2. Claim 1 is not clear in various respects (Art.6 PCT):-

2.1 Claim 1 specifies in the first lines that "a de-convolution process is applied to image-domain results of an object-scan to derive therefrom the respective point- or line-spread function of ... object discontinuities". This phrase has not been understood. While the first part of the phrase can be well understood as to address, in generic terms, a de-convolution process applied to image-domain results of an object-scan, it is not at all clear, how from a scan of a real-world object a point- or line-spread function can be obtained, as suggested in the second part of the criticized phrase.
Conventionally, the point- or line-spread function of an imaging system is determined prior to the actual object-scans of interest. The point- or line-spread function is then used, in a de-convolution step, to correct the object scans (see e.g. **D1,** page 154, or **D2,** abstract and page 153). Since, from pages 4-6 and from Fig.2 of the present application it appears that this basic de-convolution technique is also used in the context of the claimed invention, current claim 1 seems misleading in this respect.

2.2 It is not clear what exactly is meant with the last feature "sub-pixel sampling". The feature is therefore interpreted to merely mean that the whole de-convolution process is carried out at sub-pixel accuracy.

2.3 In the light of the description and on basis of general knowledge (see in particular D1 and D2) claim 1 is therefore interpreted as to recite:
A method of imaging in which a de-convolution process is applied to image-domain results of an object-scan, using an imaging system, the method comprising the steps of:-

(a) providing a point- or line-spread function (22) of the imaging system;

(b) scanning an object having a discontinuity, thereby obtaining an image of the object;

(c) deriving from the point- or line-spread function (22) the location of the discontinuity in the image,

(d) wherein the de-convolution process is carried out at sub-pixel accuracy.

3. Novelty and Inventive step.

3.1 The feature (c) of claim 1 ("to derive from said function the location ...") is broad and clearly reads onto the conventional deconvolution method in which the scan image is de-convolved with the LSF or PSF of the imaging system; this usually resulting in an edge-enhanced image from which "object discontinuities", i.e. edges, can be "derived", exactly as it is worded in the claim, see e.g. **D1:** Fig.3, or **D2:** abstract and page 153.

The last feature "sub-pixel accuracy" is known from **D1,** page 154, right hand column, lines 8-11.

It thus appears that claim 1 lacks novelty over **D1** (Art.33(2) PCT).

3.2 Document **D3** discloses edge feature extraction at sub-pixel accuracy (see abstract; page 344, col.1), and a combination of **D2 and D3** would seem to render claim 1 obvious.

It is moreover noted that, further to D3, various techniques of "sub-pixel sampling" of some kind are known in the art to improve the perceived image sharpness, and it is not apparent in what respect the broad claimed feature "sub-pixel sampling" would go beyond these conventional techniques.

4. Dependent claims.

- Claim 2: The feature "mid-point of the full-width half-maximum" of the LSF seems to be known from **D1:** page 155, col.2 and **D2:** page 157, col.1 and table II. Should there be any dispute on the disclosure of D1 and D2 in this respect, then the feature at issue would at least lack an inventive step.
- Claim 3: The limitation of the claim with respect to claim 1 and conventional deconvolution methods is not apparent.

- Claim 4: The notion of transfer of sub-pixels is not known from the prior art on file. The solution provided by claim 4 seems to enable substantial recovery of the loss of spatial resolution in the imaging, without the trade-off loss of other properties such as image noise which is often a problem in edge enhancement. While **D3** is also concerned with edge feature extraction at sub-pixel accuracy, D3 uses another approach and classifies an edge with respect to edge profiles (**D3:** abstract; page 344, col.1).
- Claim 5: Least-square filters are used in various contexts (see D2: abstract; **D3:** abstract) and the claim is too vague to provide any new effect.

Claims 6, 7: see D1, Fig.3.

Claims 8-11: The technical problems solved by subject-matter of these claims seem unrelated with that of the preceding claims in that it concerns quite different aspects of an MR or CT system. The features of the claims as such seem to be conventional in the art, and the claims therefore seem to lack an inventive step.

5. The above objections apply to the system claims accordingly.

6. Briefly, it seems that the contribution of the application over the prior art seems to reside in the particular way in which unsharp edges are restored, i.e. in the algorithm that uses transfer of sub-pixels, as specified in dependent claim 4.

*****

modulation transfer which is given by the ratio, expressed as a percentage, of the amplitude of the modulation in the image domain to that in the object domain.

The smearing effect becomes more intense as adjacent ERFs of discontinuities or contrast profiles get closer to each other (or as the spatial frequency of the modulation becomes higher); this also causes loss of profile height. The inherent loss of the spatial resolution (that is, the part that is indicated by the smeared-out effect on the corner edge of the ERF) cannot be restored or partially restored even by re-scanning the image with an ultra high resolution digital scanner system.

The further processing 5 is operative in accordance with the invention to provide accurate image-edge definition and location, and to improve spatial resolution in the imaging. More especially, in the context of Figure 2, the edge position corresponding to the discontinuity or step 23 of the object ERF is pin-pointed in the image domain from the mid-point of the full-width half-maximum (FWHM) of the image PSF; the pin-pointing is to sub-pixel accuracy for the image ERF. Low-contrast and 'area' filtering are used to remove 'spurious' edges, and sub-pixel sampling to detect detail to the resolution of the single-pixel modulation. The discontinuity or step 23 of the ERF is then restored within the image domain by removing the sub-pixel values from outside the optimum edge position to compensate for those within. It is to be noted that the sub-pixels then become pixels in display, and that the enhancement is equivalent to the performance of an extra high resolution image transfer system.

As represented in Figure 2 by the arrows 27 and 28, the image ERF 25 of an infinitely-sharp step 23 can be

produced by convolution of the image PSF 22 with the object ERF 23. In accordance with the present invention, de-convolution of the image ERF 25 using sub-pixel sampling, represented by the arrow 29, reproduces the image PSF 22 in a de-convolution space as image PSF 22'. The image ERF 25 is superimposed on the PSF 22' within this space as image ERF 25', and the optimum edge-position 30 is derived from the mid-point of the FWHM of the image PSF 22', and is pin-pointed to sub-pixel accuracy.

For one-dimensional cases, the operation in accordance with the invention is relatively simple, as only either the x- or the y-profile, that is to say a line spread function LSF is involved. But for two-dimensional operations, both the x- and y-profiles, and if necessary, the xy-diagonal profiles to eliminate any possible streakings in the image, may be used; in this case, a proper weighting scheme will be required to re-construct the image.

Once the original sharp-edge feature represented by the object ERF 23 is pin-pointed at the position 30 within further processing 5, that feature may be restored by additional re-processing 6 (Figure 1). In re-processing 6, the sub-pixel values occurring 'outside' the optimum edge-position 30 are transferred to compensate those 'within'. This is illustrated in Figure 2 by arrow 31 transferring sub-pixel blocks 32 from after point 30 in the image ERF 25', to before it. The re-construction of image ERF 25' into image ERF 33 conforming closely in configuration to object ERF 23 is represented by arrow 34. Image ERF 33 is displayed in enlarged form in display 7 (Figure 1).

These techniques enable substantial recovery of the loss of spatial resolution in the imaging, without the

trade-off loss of other properties such as image noise. Furthermore, the enhancement of spatial resolution in display 7 reproduces the region of interest selected from display 3, without blurring (or step) effects at the profile edge.

Figure 3 is illustrative of some of the low-contrast results provided in practice from MR scanning of a pig's brain in fluid. Curve A is the image ERF produced, whereas curve B is the line spread function (LSF) resulting from de-convolution of curve A carried out in processing 5. The optimum edge-position is established from the mid-point C of the FWHM of curve B, and the additional re-processing 6 is operative by means of sub-pixel transfer, to re-construct curve A to conform substantially to the edge-feature from which it originated in the display 7.

It is to be noted that whereas curve A is stepped, curve B is nonetheless smooth and that mid-point C is located to sub-pixel accuracy. Furthermore curve B indicates a sensitivity of more than 8:1 between the profile-height and background noise.

Referring again to Figure 2, the complete profile 35 of an image within the selected area of interest of display 3, is built up as indicated by arrow 36, from the edge-position data derived within processing 5. This data identifies the location of the point 30, together with the locations of all corresponding points derived from sampling the multiple x- or y-profiles of the selected area of interest. The build up and display of these points from the data takes place in display 8 so that a substantially true contour 37 for the profile 35 is defined. The sharpness of the true contour 37 is in contrast to the smeared contour that without de-convolution would have been obtained by virtue of the

Claims:

1. A method of imaging in which a de-convolution process is applied to the image-domain results of an object-scan to derive therefrom the respective point- or line-spread function of one or more object-discontinuities, and to derive from said function the location in the image domain of the respective discontinuity, wherein the de-convolution process is carried out using sub-pixel sampling.

2. A method according to Claim 1 wherein the location of the respective discontinuity is derived from the mid-point of the full-width half-maximum of said function.

3. A method according to Claim 1 or Claim 2 wherein said function is correlated with the image-domain results of said transfer for enhancement of spatial resolution of the imaging of the one or more discontinuities.

4. A method according to Claim 3 wherein the enhancement of spatial resolution of the imaging of the one or more discontinuities involves transfer of sub-pixels within the image-domain results of the respective one or more discontinuities, the sub-pixels being transferred within their respective image-domain results from one side to the other of said location for edge-image definition.

5. A method according to any one of Claims 1 to 4 wherein the de-convolution process is carried out using least-squares running filtering.

6. A method according to any one of Claims 1 to 5 wherein an edge-contour of the object is defined in the image domain using de-convolution processing as aforesaid.

7. A method according to Claim 6 wherein the area and/or volume of the object-image within the edge-contour is determined.

8. A method according to Claim 6 or Claim 7 wherein the object-scan is a magnetic resonance (MR) scan, values of relaxation times T_1 and T_2 are derived for the object-image within said contour, and these values are used to identify from stored data, types of tissue or other material involved in the scanned object.

9. A method according to Claim 8 wherein density values for the identified tissue or other material types are derived from further stored data.

10. A method of imaging according to any one of Claims 1 to 9 wherein corresponding computed tomography (CT) and magnetic resonance (MR) scans of the same part of an object are derived, the scans are related to one another for correlation of one to the other positionally with respect to said part using the de-convolution process, and imaging of said part of the object is provided in accordance with the MR scan as modified spatially in dependence upon the CT contrast numbers applicable to the corresponding, correlated positions of the CT scan.

11. A method according to any one of Claims 8 to 10 wherein geometric correction is applied to the imaging derived from the MR scan, in accordance with stored data.

12. An imaging system comprising means for performing a de-convolution process on the image-domain results of an object-scan to derive therefrom the respective point- or line-spread function of one or more object-discontinuities, and means to derive from said function the location in the image domain of the respective

discontinuity, wherein the de-convolution process is carried out using sub-pixel sampling.

13. A system according to Claim 12 wherein the location of the respective discontinuity is derived from the mid-point of the full-width half-maximum of said function.

14. A system according to Claim 12 or Claim 13 wherein said function is correlated with the image-domain results of said transfer for enhancement of spatial resolution of the imaging of the one or more discontinuities.

15. A system according to Claim 14 wherein the enhancement of spatial resolution of the imaging of the one or more discontinuities involves transfer of sub-pixels within the image-domain results of the respective one or more discontinuities, the sub-pixels being transferred within their respective image-domain results from one side to the other of said location for edge-image definition.

16. A system according to any one of Claims 12 to 15 wherein the de-convolution process is carried out using least-squares running filtering.

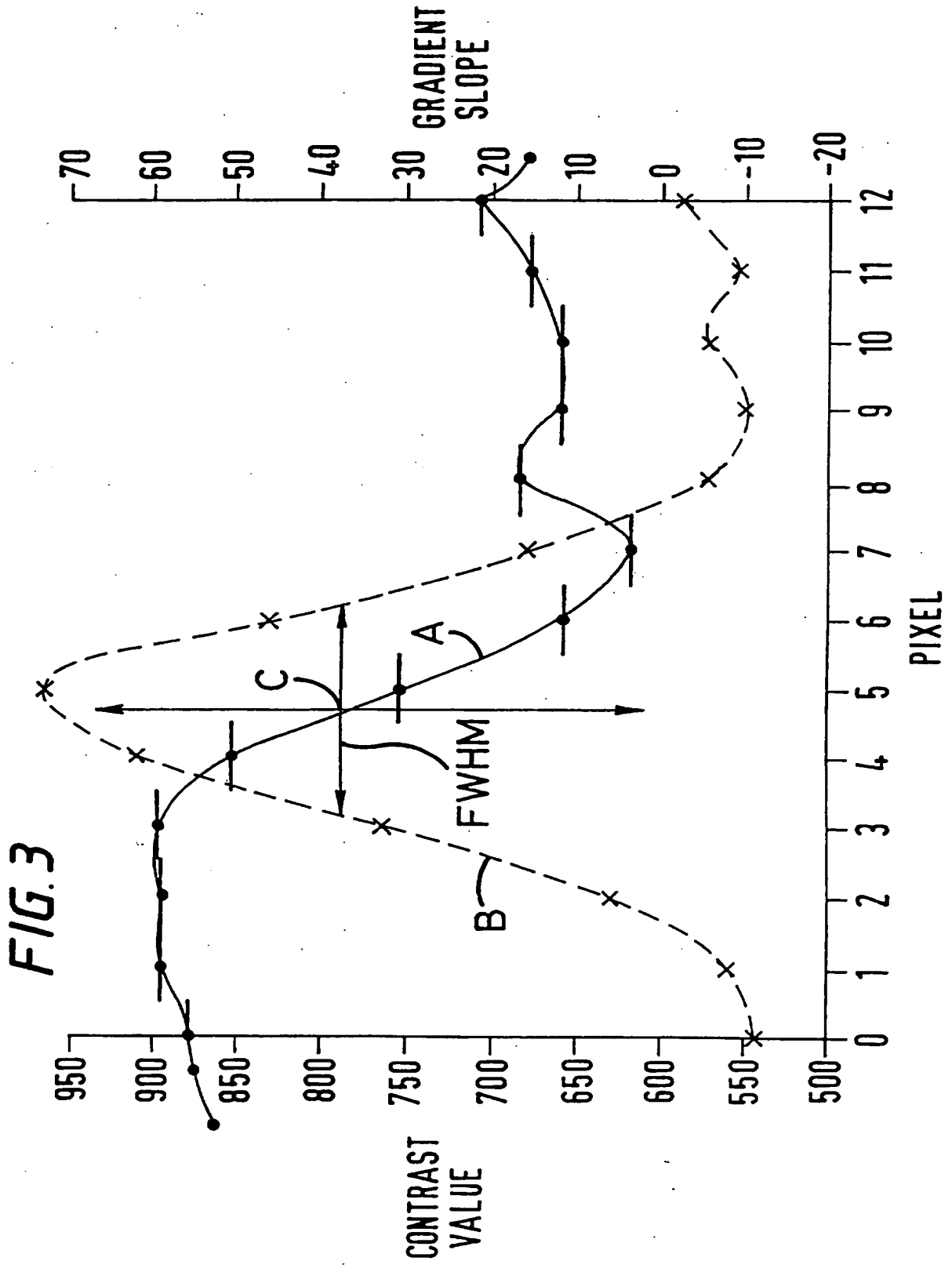

GRADIENT SLOPE
70
60
50
40
30
20
10
0
-10
-20
12
11
10
9
8
7
6
5
4
3
2
1
0
PIXEL
A
B
C
FWHM
950
900
850
800
750
700
650
600
550
500
CONTRAST VALUE

FIG. 3

PATENT COOPERATION TREATY

From the INTERNATIONAL BUREAU

PCT

NOTICE INFORMING THE APPLICANT OF THE COMMUNICATION OF THE INTERNATIONAL APPLICATION TO THE DESIGNATED OFFICES

(PCT Rule 47.1(c), first sentence)

To:
COLES, Graham, Frederick
Graham Coles & Co.
24 Seeleys Road
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ROYAUME-UNI

Date of mailing (day/month/year) 20 April 2000 (20.04.00)	
Applicant's or agent's file reference PA/GX98 PCT	**IMPORTANT NOTICE**

International application No.	**International filing date** (day/month/year)	**Priority date** (day/month/year)
PCT/GB99/03417	15 October 1999 (15.10.99)	15 October 1998 (15.10.98)

Applicant
CHUI, Kui, Ming

1. Notice is hereby given that the International Bureau has communicated, as provided in Article 20, the international application to the following designated Offices on the date indicated above as the date of mailing of this Notice:
   AU,CN,JP,KP,KR,MA,US

   In accordance with Rule 47.1(c), third sentence, those Offices will accept the present Notice as conclusive evidence that the communication of the international application has duly taken place on the date of mailing indicated above and no copy of the international application is required to be furnished by the applicant to the designated Office(s).

2. The following designated Offices have waived the requirement for such a communication at this time:
   AE,AL,AM,AP,AT,AZ,BA,BB,BG,BR,BY,CA,CH,CR,CU,CZ,DE,DK,DM,EA,EE,EP,ES,FI,GB,GD,GE,
   GH,GM,HR,HU,ID,IL,IN,IS,KE,KG,KZ,LC,LK,LR,LS,LT,LU,LV,MD,MG,MK,MN,MW,MX,NO,NZ,OA,
   PL,PT,RO,RU,SD,SE,SG,SI,SK,SL,TJ,TM,TR,TT,TZ,UA,UG,UZ,VN,YU,ZA,ZW
   The communication will be made to those Offices only upon their request. Furthermore, those Offices do not require the applicant to furnish a copy of the international application (Rule 49.1(a-bis)).

3. Enclosed with this Notice is a copy of the international application as published by the International Bureau on
   20 April 2000 (20.04.00) under No. WO 00/22573

REMINDER REGARDING CHAPTER II (Article 31(2)(a) and Rule 54.2)

If the applicant wishes to postpone entry into the national phase until 30 months (or later in some Offices) from the priority date, **a demand for international preliminary examination** must be filed with the competent International Preliminary Examining Authority before the expiration of 19 months from the priority date.

It is the applicant's sole responsibility to monitor the 19-month time limit.

Note that only an applicant who is a national or resident of a PCT Contracting State which is bound by Chapter II has the right to file a demand for international preliminary examination.

REMINDER REGARDING ENTRY INTO THE NATIONAL PHASE (Article 22 or 39(1))

If the applicant wishes to proceed with the international application in the **national phase**, he must, within 20 months or 30 months, or later in some Offices, perform the acts referred to therein before each designated or elected Office.

For further important information on the time limits and acts to be performed for entering the national phase, see the Annex to Form PCT/IB/301 (Notification of Receipt of Record Copy) and Volume II of the PCT Applicant's Guide.

The International Bureau of WIPO
34, chemin des Colombettes
1211 Geneva 20, Switzerland

Facsimile No. (41-22) 740.14.35

Authorized officer
J. Zahra

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PCT

REQUEST

The undersigned requests that the present international application be processed according to the Patent Cooperation Treaty.

For receiving Office use only

International Application No.

International Filing Date

Name of receiving Office and "PCT International Application"

Applicant's or agent's file reference *(if desired) (12 characters maximum)* PA/GX98 PCT

Box No. I TITLE OF INVENTION

IMAGING

Box No. II APPLICANT

Name and address: *(Family name followed by given name; for a legal entity, full official designation. The address must include postal code and name of country. The country of the address indicated in this Box is the applicant's State (that is, country) of residence if no State of residence is indicated below.)*

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United Kingdom

☒ This person is also inventor.

Telephone No.

Facsimile No.

Teleprinter No.

State *(that is, country)* of nationality: GB

State *(that is, country)* of residence: GB

This person is applicant for the purposes of: ☒ all designated States ☐ all designated States except the United States of America ☐ the United States of America only ☐ the States indicated in the Supplemental Box

Box No. III FURTHER APPLICANT(S) AND/OR (FURTHER) INVENTOR(S)

Name and address: *(Family name followed by given name; for a legal entity, full official designation. The address must include postal code and name of country. The country of the address indicated in this Box is the applicant's State (that is, country) of residence if no State of residence is indicated below.)*

This person is:

☐ applicant only

☐ applicant and inventor

☐ inventor only *(If this check-box is marked, do not fill in below.)*

State *(that is, country)* of nationality:

State *(that is, country)* of residence:

This person is applicant for the purposes of: ☐ all designated States ☐ all designated States except the United States of America ☐ the United States of America only ☐ the States indicated in the Supplemental Box

☐ Further applicants and/or (further) inventors are indicated on a continuation sheet.

Box No. IV AGENT OR COMMON REPRESENTATIVE; OR ADDRESS FOR CORRESPONDENCE

The person identified below is hereby/has been appointed to act on behalf of the applicant(s) before the competent International Authorities as: ☒ agent ☐ common representative

Name and address: *(Family name followed by given name; for a legal entity, full official designation. The address must include postal code and name of country.)*

COLES, Graham Frederick
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☐ **Address for correspondence: Mark this check-box where no agent or common representative is/has been appointed and the space above is used instead to indicate a special address to which correspondence should be sent.**

Box No.V DESIGNATION OF STATES

The following designations are hereby made under Rule 4.9(a) *(mark the applicable check-boxes; at least one must be marked)*:

Regional Patent

- ☒ AP ARIPO Patent: GH Ghana, GM Gambia, KE Kenya, LS Lesotho, MW Malawi, SD Sudan, SL Sierra Leone, SZ Swaziland, UG Uganda, ZW Zimbabwe, and any other State which is a Contracting State of the Harare Protocol and of the PCT
- ☒ EA Eurasian Patent: AM Armenia, AZ Azerbaijan, BY Belarus, KG Kyrgyzstan, KZ Kazakhstan, MD Republic of Moldova, RU Russian Federation, TJ Tajikistan, TM Turkmenistan, and any other State which is a Contracting State of the Eurasian Patent Convention and of the PCT
- ☒ EP European Patent: AT Austria, BE Belgium, CH and LI Switzerland and Liechtenstein, CY Cyprus, DE Germany, DK Denmark, ES Spain, FI Finland, FR France, GB United Kingdom, GR Greece, IE Ireland, IT Italy, LU Luxembourg, MC Monaco, NL Netherlands, PT Portugal, SE Sweden, and any other State which is a Contracting State of the European Patent Convention and of the PCT
- ☒ OA OAPI Patent: BF Burkina Faso, BJ Benin, CF Central African Republic, CG Congo, CI Côte d'Ivoire, CM Cameroon, GA Gabon, GN Guinea, GW Guinea-Bissau, ML Mali, MR Mauritania, NE Niger, SN Senegal, TD Chad, TG Togo, and any other State which is a member State of OAPI and a Contracting State of the PCT *(if other kind of protection or treatment desired, specify on dotted line)* .....

National Patent *(if other kind of protection or treatment desired, specify on dotted line)*:

- ☒ AE United Arab Emirates
- ☒ AL Albania
- ☒ AM Armenia
- ☒ AT Austria
- ☒ AU Australia
- ☒ AZ Azerbaijan
- ☒ BA Bosnia and Herzegovina
- ☒ BB Barbados
- ☒ BG Bulgaria
- ☒ BR Brazil
- ☒ BY Belarus
- ☒ CA Canada
- ☒ CH and LI Switzerland and Liechtenstein
- ☒ CN China
- ☒ CU Cuba
- ☒ CZ Czech Republic
- ☒ DE Germany
- ☒ DK Denmark
- ☒ EE Estonia
- ☒ ES Spain
- ☒ FI Finland
- ☒ GB United Kingdom
- ☒ GD Grenada
- ☒ GE Georgia
- ☒ GH Ghana
- ☒ GM Gambia
- ☒ HR Croatia
- ☒ HU Hungary
- ☒ ID Indonesia
- ☒ IL Israel
- ☒ IN India
- ☒ IS Iceland
- ☒ JP Japan
- ☒ KE Kenya
- ☒ KG Kyrgyzstan
- ☒ KP Democratic People's Republic of Korea
- ☒ KR Republic of Korea
- ☒ KZ Kazakhstan
- ☒ LC Saint Lucia
- ☒ LK Sri Lanka
- ☒ LR Liberia
- ☒ LS Lesotho
- ☒ LT Lithuania
- ☒ LU Luxembourg
- ☒ LV Latvia
- ☒ MD Republic of Moldova
- ☒ MG Madagascar
- ☒ MK The former Yugoslav Republic of Macedonia
- ☒ MN Mongolia
- ☒ MW Malawi
- ☒ MX Mexico
- ☒ NO Norway
- ☒ NZ New Zealand
- ☒ PL Poland
- ☒ PT Portugal
- ☒ RO Romania
- ☒ RU Russian Federation
- ☒ SD Sudan
- ☒ SE Sweden
- ☒ SG Singapore
- ☒ SI Slovenia
- ☒ SK Slovakia
- ☒ SL Sierra Leone
- ☒ TJ Tajikistan
- ☒ TM Turkmenistan
- ☒ TR Turkey
- ☒ TT Trinidad and Tobago
- ☒ UA Ukraine
- ☒ UG Uganda
- ☒ US United States of America
- ☒ UZ Uzbekistan
- ☒ VN Viet Nam
- ☒ YU Yugoslavia
- ☒ ZA South Africa
- ☒ ZW Zimbabwe

Check-boxes reserved for designating States which have become party to the PCT after issuance of this sheet:

☒ CR Costa Rica ☒ TZ United Rep of Tanzania
☒ DM Dominica ☒ MA Moroco

Precautionary Designation Statement: In addition to the designations made above, the applicant also makes under Rule 4.9(b) all other designations which would be permitted under the PCT except any designation(s) indicated in the Supplemental Box as being excluded from the scope of this statement. The applicant declares that those additional designations are subject to confirmation and that any designation which is not confirmed before the expiration of 15 months from the priority date is to be regarded as withdrawn by the applicant at the expiration of that time limit. *(Confirmation of a designation consists of the filing of a notice specifying that designation and the payment of the designation and confirmation fees. Confirmation must reach the receiving Office within the 15-month time limit.)*

Box No. VI PRIORITY CLAIM ☐ Further priority claims are indicated in the Supplemental Box.

Filing date of earlier application (day/month/year)	Number of earlier application	Where earlier application is: national application: country	regional application:* regional Office	international application: receiving Office
item (1) 15 October 1998 (15/10/98)	9822397.7	GB		
item (2) 18 November 1998 (18/11/98)	9825165.5	GB		
item (3) 02 February 1999 (02/02/99)	9902332.7	GB		

☒ The receiving Office is requested to prepare and transmit to the International Bureau a certified copy of the earlier application(s) *(only if the earlier application was filed with the Office which for the purposes of the present international application is the receiving Office)* identified above as item(s): 1-3

** Where the earlier application is an ARIPO application, it is mandatory to indicate in the Supplemental Box at least one country party to the Paris Convention for the Protection of Industrial Property for which that earlier application was filed (Rule 4.10(b)(ii)). See Supplemental Box.*

Box No. VII INTERNATIONAL SEARCHING AUTHORITY

Choice of International Searching Authority (ISA) *(if two or more International Searching Authorities are competent to carry out the international search, indicate the Authority chosen; the two-letter code may be used):*
ISA/

Request to use results of earlier search; reference to that search *(if an earlier search has been carried out by or requested from the International Searching Authority):*
Date *(day/month/year)* Number Country *(or regional Office)*

Box No. VIII CHECK LIST; LANGUAGE OF FILING

This international application contains the following number of sheets:

request	:	3
description (excluding sequence listing part)	:	18
claims	:	3
abstract	:	1
drawings	:	6
sequence listing part of description	:	
Total number of sheets	:	31

This international application is **accompanied** by the item(s) marked below:

1. ☐ fee calculation sheet
2. ☐ separate signed power of attorney
3. ☐ copy of general power of attorney; reference number, if any:
4. ☐ statement explaining lack of signature
5. ☐ priority document(s) identified in Box No. VI as item(s):
6. ☐ translation of international application into (language):
7. ☐ separate indications concerning deposited microorganism or other biological material
8. ☐ nucleotide and/or amino acid sequence listing in computer readable form
9. ☒ other *(specify)*: General Power of Attorney

Figure of the drawings which should accompany the abstract: 2

Language of filing of the international application: ENGLISH

Box No. IX SIGNATURE OF APPLICANT OR AGENT

Next to each signature, indicate the name of the person signing and the capacity in which the person signs (if such capacity is not obvious from reading the request).

COLES, Graham Frederick

For receiving Office use only

1. Date of actual receipt of the purported international application:
2. Drawings: ☐ received: ☐ not received:
3. Corrected date of actual receipt due to later but timely received papers or drawings completing the purported international application:
4. Date of timely receipt of the required corrections under PCT Article 11(2):
5. International Searching Authority (if two or more are competent): ISA/
6. ☐ Transmittal of search copy delayed until search fee is paid.

For International Bureau use only

Date of receipt of the record copy by the International Bureau:

REPLACED BY ART 34 AMDT

WO 00/22573

09/807396
Rec'd PCT/PTO 12 APR 2001
PCT/GB99/03417

Imaging

This invention relates to imaging and in particular to methods and systems for image enhancement.

Imaging involves transfer from the object domain into the image domain, but owing to limiting factors such as the finite size of energy source, detector size, sampling frequency, display density, software filter function, and possibly partial-volume effects experienced with some imagers, an infinitely fine delta function in the object domain cannot be faithfully reproduced in the image domain. Instead, a smeared-out image, or point-spread function (PSF), is observed. Similarly, an infinitely sharp edge-response function (ERF) in the object domain becomes a smeared-out ERF in the image domain. The smearing effect becomes more intense as the adjacent ERFs of discontinuities or contrast profiles get closer to each other.

It is an object of the present invention to provide a method and system by which the above problem can be at least partly overcome.

According to one aspect of the present invention there is provided a method wherein a de-convolution process is applied to the image-domain results of an object-scan to derive therefrom the respective point- or line-spread function effective in the object- to image-domain transfer of one or more object-discontinuities, and to derive from said function the location in the image domain of the respective discontinuity.

According to another aspect of the invention there is provided an imaging system comprising means for

performing a de-convolution process on the image-domain results of an object-scan to derive therefrom the respective point- or line-spread function effective in the object- to image-domain transfer of one or more object-discontinuities, and means to derive from said function the location in the image domain of the respective discontinuity.

The method and system of the invention enable the location of the respective discontinuity in the image domain, to be established with a high degree of accuracy. This is critical to image definition free of any substantial smearing, and to this end the location of the respective discontinuity may be derived to sub-pixel accuracy simply from the mid-point of the full-width half-maximum of said function.

The said function may be correlated with the image-domain results of said transfer for enhancement of spatial resolution of the imaging of the one or more discontinuities. This enhancement may involve transfer of sub-pixels within the image-domain results of the respective one or more discontinuities, the sub-pixels being transferred within their respective image-domain results from one side to the other of said location.

The de-convolution process may be carried out using least-squares running filtering.

An imaging method and system according to the present invention will now be described, by way of example, with reference to the accompanying drawings, in which:

Figure 1 illustrates schematically the method and system of the invention;

modulation transfer which is given by the ratio, expressed as a percentage, of the amplitude of the modulation in the image domain to that in the object domain.

The smearing effect becomes more intense as adjacent ERFs of discontinuities or contrast profiles get closer to each other (or as the spatial frequency of the modulation becomes higher); this also causes loss of profile height. The inherent loss of the spatial resolution (that is, the part that is indicated by the smeared-out effect on the corner edge of the ERF) cannot be restored or partially restored even by re-scanning the image with an ultra high resolution digital scanner system.

The further processing 5 is operative in accordance with the invention to provide accurate image-edge definition and location, and to improve spatial resolution in the imaging. More especially, in the context of Figure 2, the edge position corresponding to the discontinuity or step 23 of the object ERF is pin-pointed in the image domain from the mid-point of the full-width half-maximum (FWHM) of the image PSF; the pin-pointing may be to sub-pixel accuracy for the image ERF. In a practical implementation, low-contrast filtering, 'area' filtering, and sub-pixel sampling may be used to remove the 'spurious' edges and other features of the single-pixel modulation. The discontinuity or step 23 of the ERF is then restored within the image domain by removing the sub-pixel values from outside the optimum edge position to compensate for those within. It is to be noted that the sub-pixels then become pixels in display, and that the enhancement is equivalent to the performance of an extra high resolution image transfer system.

As represented in Figure 2 by the arrows 27 and 28, the image ERF 25 of an infinitely-sharp ERF 23 can be

produced by convolution of the image PSF 22 with the object ERF 23. In accordance with the present invention, de-convolution of the image ERF 25 represented by the arrow 29 reproduces the image PSF 22 in a de-convolution space as image PSF 22'. The image ERF 25 is superimposed on the PSF 22' within this space as image ERF 25', and the optimum edge-position 30 is derived from the mid-point of the FWHM of the image PSF 22', and is pin-pointed to sub-pixel accuracy.

For one-dimensional cases, the operation in accordance with the invention is relatively simple, as only either the x- or the y-profile, that is to say a line spread function LSF is involved. But for two-dimensional operations, both the x- and y-profiles, and if necessary, the xy-diagonal profiles to eliminate any possible streakings in the image, may be used; in this case, a proper weighting scheme will be required to re-construct the image.

Once the original sharp-edge feature represented by the object ERF 23 is pin-pointed at the position 30 within further processing 5, that feature may be restored by additional re-processing 6 (Figure 1). In re-processing 6, the sub-pixel values occurring 'outside' the optimum edge-position 30 are transferred to compensate those 'within'. This is illustrated in Figure 2 by arrow 31 transferring sub-pixel blocks 32 from after point 30 in the image ERF 25', to before it. The re-construction of image ERF 25' into image ERF 33 conforming closely in configuration to object ERF 23 is represented by arrow 34. Image ERF 33 is displayed in enlarged form in display 7 (Figure 1).

These techniques enable substantial recovery of the loss of spatial resolution in the imaging, without the trade-off loss of other properties such as image noise.

Furthermore, the enhancement of spatial resolution in display 7 reproduces the region of interest selected from display 3, without blurring (or step) effects at the profile edge.

Figure 3 is illustrative of some of the low-contrast results provided in practice from MR scanning of a pig's brain in fluid. Curve A is the image ERF produced, whereas curve B is the line spread function (LSF) resulting from de-convolution of curve A carried out in processing 5. The optimum edge-position is established from the mid-point C of the FWHM of curve B, and the additional re-processing 6 is operative by means of sub-pixel transfer, to re-construct curve A to conforms substantially to the edge-feature from which it originated in the display 7.

It is to be noted that whereas curve A is stepped, curve B is nonetheless smooth and that mid-point C is located to sub-pixel accuracy. Furthermore curve B indicates a sensitivity of more than 8:1 between the profile-height and background noise.

Referring again to Figure 2, the complete profile 35 of an image within the selected area of interest of display 3, is built up as indicated by arrow 36, from the edge-position data derived within processing 5. This data identifies the location of the point 30, together with the locations of all corresponding points derived from sampling the multiple x- or y-profiles of the selected area of interest. The build up and display of these points from the data takes place in display 8 so that a substantially true contour 37 for the profile 35 is defined. The sharpness of the true contour 37 is in contrast to the smeared contour that without de-convolution would have been obtained by virtue of the

Claims:

1. A method of imaging wherein a de-convolution process is applied to the image-domain results of an object-scan to derive therefrom the respective point- or line-spread function effective in the object- to image-domain transfer of one or more object-discontinuities, and to derive from said function the location in the image domain of the respective discontinuity.

2. A method according to Claim 1 wherein the location of the respective discontinuity is derived from the mid-point of the full-width half-maximum of said function.

3. A method according to Claim 1 or Claim 2 wherein said function is correlated with the image-domain results of said transfer for enhancement of spatial resolution of the imaging of the one or more discontinuities.

4. A method according to Claim 3 wherein the enhancement of spatial resolution of the imaging of the one or more discontinuities involves transfer of sub-pixels within the image-domain results of the respective one or more discontinuities, the sub-pixels being transferred within their respective image-domain results from one side to the other of said location.

5. A method according to any one of Claims 1 to 4 wherein the de-convolution process is carried out using least-squares running filtering.

6. A method according to any one of Claims 1 to 5 wherein an edge-contour of the object is defined in the image domain using de-convolution processing as aforesaid.

7. A method according to Claim 6 wherein the area and/or volume of the object-image within the edge-contour is determined.

8. A method according to Claim 6 or Claim 7 wherein the object-scan is a magnetic resonance (MR) scan, values of relaxation times T_1 and T_2 are derived for the object-image within said contour, and these values are used to identify from stored data, types of tissue or other material involved in the scanned object.

9. A method according to Claim 8 wherein density values for the identified tissue or other material types are derived from further stored data.

10. A method of imaging according to any one of Claims 1 to 9 wherein corresponding computed tomography (CT) and magnetic resonance (MR) scans of the same part of an object are derived, the scans are related to one another for correlation of one to the other positionally with respect to said part using the de-convolution process, and imaging of said part of the object is provided in accordance with the MR scan as modified spatially in dependence upon the CT contrast numbers applicable to the corresponding, correlated positions of the CT scan.

11. A method according to any one of Claims 8 to 10 wherein geometric correction is applied to the imaging derived from the MR scan, in accordance with stored data.

12. An imaging system comprising means for performing a de-convolution process on the image-domain results of an object-scan to derive therefrom the respective point- or line-spread function effective in the object- to image-domain transfer of one or more object-discontinuities, and means to derive from said function the location in the image domain of the respective discontinuity.

13. A system according to Claim 12 wherein the location of the respective discontinuity is derived from the mid-point of the full-width half-maximum of said function.

14. A system according to Claim 12 or Claim 13 wherein said function is correlated with the image-domain results of said transfer for enhancement of spatial resolution of the imaging of the one or more discontinuities.

15. A method according to Claim 14 wherein the enhancement of spatial resolution of the imaging of the one or more discontinuities involves transfer of sub-pixels within the image-domain results of the respective one or more discontinuities, the sub-pixels being transferred within their respective image-domain results from one side to the other of said location.

16. A system according to any one of Claims 12 to 15 wherein the de-convolution process is carried out using least-squares running filtering.

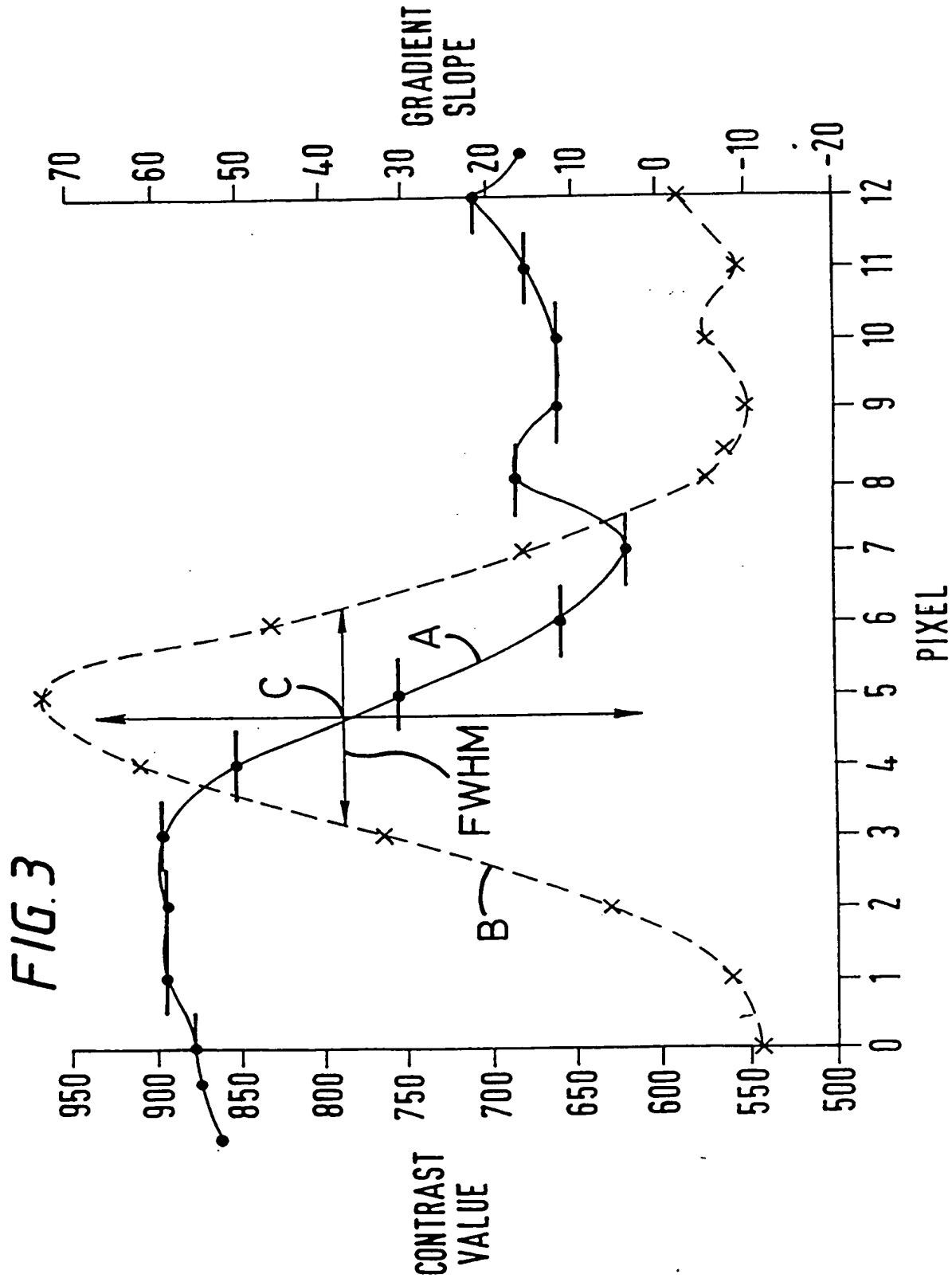
GRADIENT SLOPE
70
60
50
40
30
20
10
0
-10
-20
CONTRAST VALUE
950
900
850
800
750
700
650
600
550
500
PIXEL
0
1
2
3
4
5
6
7
8
9
10
11
12
A
B
C
FWHM

FIG. 3